

# Detection of the detached dust shell of U Antliae at mid-infrared wavelengths with AKARI/IRC

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## ABSTRACT

We report mid-infrared (MIR) imaging observations of the carbon star U Ant made with the Infrared Camera (IRC) on board *AKARI*. Subtraction of the artifacts and extended PSF of the central star reveals the detached dust shell around the carbon star at MIR wavelengths (15 and 24  $\mu\text{m}$ ) for the first time. The observed radial brightness profiles of the MIR emission are well explained by two shells at 43'' and 50'' from the central star detected in optical scattered light observations. Combining *Herschel*/PACS, *AKARI*/FIS, and *AKARI*/IRC data, we obtain the infrared spectral energy distribution (SED) of the thermal emission from the detached shell of U Ant in a wide infrared spectral range of 15–160  $\mu\text{m}$ . Thermal emission of amorphous carbon grains with a single temperature cannot account for the observed SED from 15 to 160  $\mu\text{m}$ : it underestimates the emission at 15  $\mu\text{m}$ . Alternatively, the observed SED is fitted by the model that amorphous carbon grains in the two shells have different temperatures of 60 and 104 K, which allocates most dust mass in the shell at 50''. This supports previous suggestion that the 43'' shell is gas-rich and the 50'' one is dust-rich. We suggest a possibility that the segregation of the gas and dust resulting from the drift motion of submicron-sized dust grains relative to the gas and that the hot dust component associated with the gas-rich shell is composed of very small grains that are strongly coupled with the gas.

*Subject headings:* stars: AGB and post-AGB — stars: carbon — stars: mass-loss — infrared: stars

## 1. Introduction

Mass loss from Asymptotic Giant Branch (AGB) stars is one of the major stellar sources that supply dust grains to the interstellar medium (ISM) and is a key process of the material circulation in galaxies (Draine 2009). AGB stars are suggested to be efficient sources even in low metallicity environments (Sloan et al. 2009). Mass loss is also crucial to the late evolutionary stages of low- to intermediate-mass stars. Radiation pressure on forming dust grains is thought to play a significant role as a mass-loss mechanism, but there still remain several open issues, such as the trigger of the mass-loss process, the dependence of the mass loss on the stellar parameters, and the change of the mass loss along the stellar evolution (Habing 1996). Far-infrared (FIR) studies based on *IRAS* observations indicate the presence of detached shells around carbon stars, suggesting that the mass-loss process is sporadic rather than steady due to thermal pulses in the star (Willems & de Jong 1988; van der Veen & Habing 1988). Detailed analyses of FIR data in fact confirm the presence of detached shells in several AGB stars (Waters et al. 1994; Izumiura et al. 1996, 1997, 2010; Ueta et al. 2010; Ladjal et al. 2010). Detached shells are also investigated in detail with CO line observations (Yamamura et al. 1993; Olofsson et al. 1996, 2000; Lindqvist et al. 1999; Schöier et al. 2005) and their spatial structures are studied in optical scattered light (González Delgado et al. 2001, 2003; Maercker et al. 2010). While CO and optical scattered-light observations provide detailed information on the shell dynamics and structure, infrared observations yield estimates of the dust mass and temperature of the detached shell. Mid-infrared (MIR) data can add crucial constraints on the temperature and mass of dust grains because they measure the Wien side of the thermal emission from the detached shell. However, no detached shells of AGB stars have so far been detected in the MIR.

U Ant is an N-type carbon star of irregular variability at a distance of 260 pc

(Knapp et al. 2003). The circumstellar envelope around U Ant is studied in the FIR (Izumiura et al. 1997), the CO emission (Olofsson et al. 1996; Maercker et al. 2010), and the optical scattered light (González Delgado et al. 2001, 2003; Maercker et al. 2010). These studies resolve 5 shells at  $\sim 25''$ ,  $37''$ ,  $43''$ ,  $50''$ , and  $3'$  from the central star (hereafter shell 1, 2, 3, 4, and 5, respectively). Maercker et al. (2010) argued that there is no strong evidence for the existence of full shells inside shell 3. Very recently the shell around U Ant is studied with PACS (Poglitch et al. 2010) onboard *Herschel Space Observatory* (Pilbratt et al. 2010), which resolves the detached shell clearly in the FIR (Kerschbaum et al. 2010). In this *Letter*, we report the first detection of the detached shell around U Ant at MIR wavelengths with the Infrared Camera (IRC; Onaka et al. 2007) onboard *AKARI* (Murakami et al. 2007). The observations are made under the *AKARI* mission program “Excavating Mass Loss History in Extended Dust Shells of Evolved Stars” (MLHES, PI: I. Y.).

## 2. Observations and Data Reduction

Observations of U Ant were made in the L15 ( $15\mu\text{m}$ ) and L24 ( $24\mu\text{m}$ ) bands of the IRC on 2006 December 20. The FWHM of the point spread function (PSF) is  $4''.7$  and  $6''.8$  for L15 and L24, respectively. The obtained dataset consists of long- and short-exposure images. Since U Ant is very bright in the MIR ( $\sim 100\text{ Jy}$  at  $15\mu\text{m}$ ), the long-exposure images are all saturated around the central star position and several artifacts appear in the images due to reflections between the optical elements of the IRC (Lorente et al. 2008). We use the short-exposure data to complement the saturated inner region and employ the long-exposure data to investigate the outer region. The short-exposure data of L24 are not saturated even at the central star, but those of L15 are nearly at the saturation level. Thus the very central part ( $r < 7''$ ) of the L15 image is not used in the following analysis. The short- and long-exposure data are smoothly connected at the unsaturated region by scaling

with the exposure time. (a factor of 28).

Accurate determination of the artifacts and the PSFs with a large dynamic range are needed to detect faint emission from the detached shell. We employed the data of the bright star IRAS 22396–4708 taken in the MLHES program as a calibration source, the archival data of CRL618 of an Open Time program, and IRAS F06009–6636 taken in the IRC calibration observations to investigate the artifacts and PSFs. The first two objects were used to investigate the artifacts and the PSFs in the outer part, while the last one was used to determine the inner PSFs, where the former data were saturated. The artifacts show movement patterns different from real objects in the image. Using this characteristic, we separated the artifacts from the PSF. Details of the procedure will be given in a separate paper. We determined the PSFs down to  $10^{-6}$  of the peak brightness both at the L15 and L24 bands (Figs. 1b and e). The PSFs of the IRC MIR images are extended over the entire field-of-view due to the scattering within the detector array as recognized in the IRAC onboard *Spitzer* (Fazio et al. 2004), which uses the same type of the detector array (Reach et al. 2005). Correction for the artifacts was applied for each exposure frame after the sky background had been subtracted. Except for this additional process, the data were reduced by the standard imaging process with the latest flat data and the dithered images were co-added to obtain the final images (Figs. 1a and d). The obtained PSFs were fitted to the inner  $20''$  region of the co-added images and subtracted (Figs. 1c and f). The scaling of the PSFs is determined with an accuracy better than 0.5%. Extended structures due to the PSF patterns produced by the central star are cancelled out almost completely and the detached shell appears clearly in the central-star-subtracted images of both bands. The PSF well fits the image both at the inside and outside of the shell, confirming the detection of the shell at L15 and L24.

U Ant was also observed with the Far-Infrared Surveyor (FIS, Kawada et al. 2007)

onboard *AKARI* on 2006 December 21 with the slow scan mode for a compact source. Data in four FIR bands, N60 ( $65\,\mu\text{m}$ ), WIDE-S ( $90\,\mu\text{m}$ ), WIDE-L ( $140\,\mu\text{m}$ ), and N160 ( $160\,\mu\text{m}$ ) were simultaneously obtained for a  $10' \times 40'$  area. The FIS data were processed in the same manner as described in Izumiura et al. (2010) and the same PSF subtraction procedure was applied as for the IRC data. The FIS data are in agreement with the IRAS and PACS data within the uncertainties and have finer spectral sampling than them. The observational data used in this study, including the calibration data, are summarized in Table 1.

### 3. Results

The central-star-subtracted image of L24 shows a smooth, symmetrical shell. The shell is also clearly seen at L15 (Figs. 1c and f). The presence of an extended component is evident even in the original L24 image (Fig. 1d), when compared to the PSF (Fig. 1e). The brightness peaks at around  $41''$  in the both bands. To investigate the shell structure in detail, we assume that the shell is optically thin at MIR and spherically symmetric. We integrate the flux density in each projected annulus to obtain the 1-D radial brightness profile (RBP). The density distribution of the shell along the radial direction is approximated by a Gaussian according to Maercker et al. (2010). The model emission is integrated along the line of sight, convolved with the PSF, and compared with the observed profile. We found that any single Gaussian distribution cannot give a reasonable fit with the observations and that the double shell with the Gaussian parameters of shell 3 and 4 estimated in Maercker et al. (2010) fits the observations fairly well.

Figures 2a and b show the double-shell model fit. The model fit parameters are summarized in Table 2. The errors in the RBP are estimated from the variance of the intensity in each annulus, which includes the error in the central star subtraction, the background sky fluctuation, and the deviation from the spherical symmetry. Although the

MIR images do not resolve the second shell, the tail of the RBP at larger radii requires a second Gaussian component whose peak is located at around  $50''$ , especially at L24. The flux densities of both shells are estimated from the Gaussian parameters. The total shell fluxes at the FIS bands are estimated by the same procedure as for the IRC. The flux density of each shell cannot be determined separately at the FIS bands because of the low spatial resolution.

Together with the FIS and PACS (Kerschbaum et al. 2010) data, we now obtain the spectral energy distribution (SED) of the detached shell of U Ant from  $15\mu\text{m}$  to  $160\mu\text{m}$ , from which the temperature and mass of dust grains in the shell can be estimated. We assume that the variability at IR wavelengths is negligible because the visual magnitude amplitude is only about 1 mag. First we assume that dust grains in the both shells have the same temperature. The PACS data are given only for the sum of the flux densities of the central star and the shells, whereas the IRC and FIS data are available for the central source and the shells separately. Thus we estimate the dust temperature and mass by minimizing

$$\chi^2 = \sum_{i=1}^6 \frac{(F_{\nu}^c(\lambda_i) - A\lambda_i^{-2})^2}{\sigma_i^2} + \sum_{i=1}^6 \frac{(F_{\nu}^s(\lambda_i) - C\lambda_i^{-\beta}B_{\nu}(\lambda_i, T))^2}{\sigma_i^2} + \sum_{i=7}^8 \frac{(F_{\nu}^t(\lambda_i) - A\lambda_i^{-2} - C\lambda_i^{-\beta}B_{\nu}(\lambda_i, T))^2}{\sigma_i^2}, \quad (1)$$

where  $B_{\nu}(\lambda, T)$  is the Planck function of the temperature  $T$ ,  $F_{\nu}^c(\lambda_i)$ ,  $F_{\nu}^s(\lambda_i)$ , and  $F_{\nu}^t(\lambda_i)$  are the observed flux densities of the central source, the shells, and the sum of the central source and the shells, respectively, at the wavelength  $i$ :  $i=1, 2, 3, 4, 5, 6, 7$ , and  $8$  correspond to  $15, 24$  (IRC),  $65, 90, 140, 160$  (FIS), and  $70$ , and  $160\mu\text{m}$  (PACS), respectively. The flux densities of the central source are estimated from the PSF fit, which include those from the star and the circumstellar envelope produced by the present mass-loss. We assume that flux densities are in the Rayleigh-Jeans regime in the spectral range in question. The

dust emissivity is assumed to be given by  $\lambda^{-\beta}$ . In Eq. (1),  $T$ ,  $A$ , and  $C$  are the fitting parameters, where  $T$  is the dust temperature and  $A$  and  $C$  are the scaling factor for the central source and the shell emission, respectively. In the fitting, we take account of the color corrections of each filter band (see Fig. 3).

The dust mass  $M$  can be estimated from

$$M = \frac{D^2}{\kappa(\lambda)} \lambda^{-\beta} C, \quad (2)$$

where  $D$  is the distance to the star (260 pc) and  $\kappa(\lambda)$  is the dust mass absorption coefficient. The dust mass given by Eq. (2) is independent of the dust size when the dust size is much smaller than the wavelength in question. We adopt the dust parameters employed in Izumiura et al. (1997) as  $\beta = 1.4$  and  $\kappa(60 \mu\text{m}) = 150 \text{ cm}^2 \text{ g}^{-1}$ . They are in agreement with those of amorphous carbon grains with the specific density of  $1.5 \text{ g cm}^{-3}$  (Suh 2000).

The best fit result for the single-temperature case is shown in Fig. 3a, which gives  $T = 75.4_{-2.3}^{+2.0} \text{ K}$  and  $M = 4.3_{-0.8}^{+1.3} \times 10^{-6} M_{\odot}$ . The single-temperature model cannot fit the observed SED well. The reduced  $\chi^2$  is 6.6, which arises mostly from excess emission at  $15 \mu\text{m}$ . If the data point of  $15 \mu\text{m}$  is removed from the fit, the reduced  $\chi^2$  improves to be 1.9 and the model underestimates the observed flux density at  $15 \mu\text{m}$  by a factor of 3.

Alternatively, we assume that dust grains in each shell (shell 3 and 4) have different temperatures. The same shell parameters adopted by Maercker et al. (2010) (Table 2) are assumed. Using the flux densities obtained for each shell at the IRC bands, we derive the best fit parameters for the two-shell model in a manner similar to Eq. (1). The best fit result for the two-shell model is shown in Fig. 3b and its parameters are given in Table 2. The reduced  $\chi^2$  becomes 1.5. The fit is significantly improved compared to the single-temperature model. The model flux density at  $15 \mu\text{m}$  agrees with the observation within the uncertainty. The two-shell model well accounts for the observed SED from 15 to  $160 \mu\text{m}$ .

#### 4. Discussion

Optical scattered light observations indicate the presence of 4 detached shells around U Ant (González Delgado et al. 2001, 2003; Maercker et al. 2010), among which the present observations detect MIR emission from shells 3 and 4. Shells 1 and 2 are seen only at the bands that contain the NaD lines and not full shells (Maercker et al. 2010). It is not clear whether these are real shells or merely patchiness present in shells 3 and 4. Optical polarization images of dust-scattered light, line-scattered light data, and medium-resolution CO radio line observations suggest that shell 3 is gas-rich and most dust grains reside in shell 4. Our results indicate that shell 4 dominates in the dust mass (Table 2), confirming their results. Izumiura et al. (1997) detect FIR emission from the detached shell at  $\sim 50''$  at 60 and  $100\,\mu\text{m}$  as well as that at  $\sim 3'$  around U Ant. They estimate the dust mass associated with the shell at  $\sim 50''$  as  $2.2 \times 10^{-5} M_{\odot}$ , which is in good agreement with the present estimate of  $1.6 \times 10^{-5} M_{\odot}$ . Maercker et al. (2010) derive the gas mass in shell 3 as  $2 \times 10^{-3} M_{\odot}$  from CO observations and the dust mass in shell 4 as  $5 \times 10^{-5} M_{\odot}$  from polarization observations. The dust mass in shell 4 derived in the present study agrees with their result, taking account of the large uncertainty in the estimation from polarization observations. The dust-to-gas ratio in shell 3 is thus  $8 \times 10^{-5}$ , supporting that shell 3 is dust-poor. The total dust-to-gas ratio for the sum of shells 3 and 4 is 0.008, which is in a reasonable range for carbon-rich AGB stars.

Adopting the distance of 260 pc, the locations of shells 3 and 4 are  $1.7 \times 10^{17}$  and  $1.9 \times 10^{17}$  cm from the star, respectively. The dynamical age of shell 3 is estimated as 2700 yr from the CO line velocity of  $19.5\,\text{km s}^{-1}$  (Maercker et al. 2010). The width of shell 3 indicates that the average mass-loss rate was  $1.2 \times 10^{-7} M_{\odot} \text{yr}^{-1}$  at the shell formation. It should be noted that this includes the swept-up material and the shell may have widened.

Detached shells around U Ant are resolved in PACS maps at 70 and  $160\,\mu\text{m}$ . The

peak intensity is located at around  $43''$  and they attribute it to shell 3 (Kerschbaum et al. 2010). The present analysis suggests that the FIR emission arises mostly from shell 4 with a negligible contribution from shell 3. We calculate the RBP of the FIR emission by adopting the same radial dust density distributions as required to explain the MIR emission (Table 2) and assigning the flux densities derived from the SED fit to each shell. Then it is convolved with the model PSF of PACS<sup>1</sup>. Figure 2c plots the result. The intensity peaks at around  $\sim 44''$  and shows a broad profile similar to the observations, which also suggest the presence of an extended emission component beyond shell 3 (Kerschbaum et al. 2010). Because the column density peaks at the inner part of the shell on the line-of-sight and shell 4 has a relatively large FWHM, the peak of the RBP is shifted to a position inside the actual shell location. Therefore, the two-shell model explains the observed RBPs and SED from 15 to  $160\,\mu\text{m}$  consistently.

If amorphous carbon grains of  $0.1\,\mu\text{m}$  size located at  $1.9 \times 10^{17}\text{ cm}$  from the star are heated by a star of  $5800\text{ L}_\odot$  (Schöier et al. 2005), their temperature will be about 70 K, which is marginally in agreement with the derived temperature of 60 K. On the other hand, the temperature of shell 3 ( $\gtrsim 100\text{ K}$ ) is definitely too hot since the estimated temperature at shell 3 is only 76 K. The dust drift with respect to the gas as an explanation for the two-shell structure was suggested by González Delgado et al. (2003) and further elaborated on by Maercker et al. (2010). The estimated drift velocity is  $3\text{ km s}^{-1}$ . In a steady state, the drift velocity  $v_d$  is given by

$$v_d = \sqrt{\frac{v_g Q_p L}{c \dot{M}}}, \quad (3)$$

where  $v_g$  is the gas velocity,  $L$  is the stellar luminosity,  $\dot{M}$  is the mass loss rate,  $c$  is the velocity of light, and  $Q_p$  is the radiation pressure efficiency factor, which is proportional to  $a$ , if  $a$  is much smaller than the wavelength (Habing et al. 1994). Thus small grains

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<sup>1</sup>[http://dirty.as.arizona.edu/~kgordon/mips/conv\\_psf/conv\\_psfs.html](http://dirty.as.arizona.edu/~kgordon/mips/conv_psf/conv_psfs.html)

have a low drift velocity. If grains of  $0.1\ \mu\text{m}$  have a drift velocity of  $3\ \text{km s}^{-1}$ , that of  $10\ \text{nm}$  grains will be  $1\ \text{km s}^{-1}$ . This makes only a  $2''$  offset in the dust distribution relative to gas in  $2700\ \text{yr}$ , which cannot be resolved clearly in the present observations. Carbonaceous grains of  $10\ \text{nm}$  have small heat capacity and will be heated up to  $100\ \text{K}$  if they absorb a photon of  $1\ \text{eV}$  by the temperature fluctuation mechanism (e.g., Aannestad 1989). Thus shell 3 can still retain very small grains, whose temperature can be quite high. These crude estimates suggest a possibility that smallest grains are still trapped in the gas-rich shell 3 and emit hot MIR radiation. The actual relative motion between the gas and dust and the temperature of very small grains need to be investigated by numerical simulations for a given size distribution of dust grains.

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*Facilities:* AKARI.

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Table 1: List of the observational data.

Observation ID	AOT <sup>a</sup>	Date	Object	Note <sup>b</sup>
1710071.1	IRC02 a;L	2006-12-20	U Ant	target
1710072.1	FIS01 1.0;15;70	2006-12-21	U Ant	target
1711365.1	IRC02 a;L	2007-05-12	IRAS 22396–4708	PSF & SCL
1710039.1	FIS01 0.5;15;70	2006-11-14	IRAS 22396–4708	PSF
4080019.1	IRC03 a;L	2007-03-05	CRL618	SCL
5124089.1	IRC03 a;L	2007-06-19	IRAS F06009–6636	PSF
5124090.1	IRC03 a;L	2007-06-22	IRAS F06009–6636	PSF
5124091.1	IRC03 a;L	2007-06-22	IRAS F06009–6636	PSF
5124092.1	IRC03 a;L	2007-06-21	IRAS F06009–6636	PSF
5124097.1	IRC03 a;L	2007-07-01	IRAS F06009–6636	PSF
5124098.1	IRC03 a;L	2007-07-04	IRAS F06009–6636	PSF
5124099.1	IRC03 a;L	2007-07-04	IRAS F06009–6636	PSF
5124100.1	IRC03 a;L	2007-07-05	IRAS F06009–6636	PSF
5124105.1	IRC03 a;L	2007-07-12	IRAS F06009–6636	PSF

<sup>a</sup>Astronomical Observation Template for the IRC and FIS observations. See ASTRO-F Observer’s Manual for details of the parameters (<http://www.ir.isas.jaxa.jp/AKARI/Observation/ObsMan/>).

<sup>b</sup>PSF indicates the data that were used to derive the PSF. SCL indicates those used to estimate the scattered light contribution (artifacts).

Table 2: Parameters of the shell.

	Shell 3 <sup>a</sup>	Shell 4 <sup>a</sup>	Total
Radial brightness profile (RBP) model			
Center position <sup>b</sup>	43''.5	49''.7	—
FHWM <sup>b</sup>	2''.2	6''.5	—
Observed flux density (Jy)			
IRC/L15	$0.68 \pm 0.11$	$0.16^{+1.0}_{-0.9}$	$0.84 \pm 0.05$
IRC/L24	$2.30 \pm 0.22$	$2.37 \pm 0.23$	$4.67 \pm 0.22$
FIS/N65	—	—	$25.8^{+5.3}_{-3.1}$
FIS/WIDE-S	—	—	$20.1 \pm 4.2$
FIS/WIDE-L	—	—	$8.4 \pm 3.1$
FIS/N160	—	—	$3.5 \pm 2.2$
PACS70	—	—	$(24.2^{+0.5}_{-0.9})^c$
PACS160	—	—	$(5.8^{+0.4}_{-0.5})^c$
SED model results <sup>d</sup>			
Temperature (K)	$103.6 \pm 7.4$	$60.0^{+1.6}_{-1.8}$	—
Dust mass ( $M_{\odot}$ )	$1.9^{+1.3}_{-0.72} \times 10^{-7}$	$1.60^{+0.22}_{-0.19} \times 10^{-5}$	$1.62^{+0.22}_{-0.19} \times 10^{-5}$

<sup>a</sup>The designation of the shells follows González Delgado et al. (2001) and Maercker et al. (2010).

<sup>b</sup>The RBP parameters are adopted from Maercker et al. (2010).

<sup>c</sup>Estimated values by subtracting the stellar flux density from the observations (see §3).

<sup>d</sup>Results of the two-shell model (see §3).

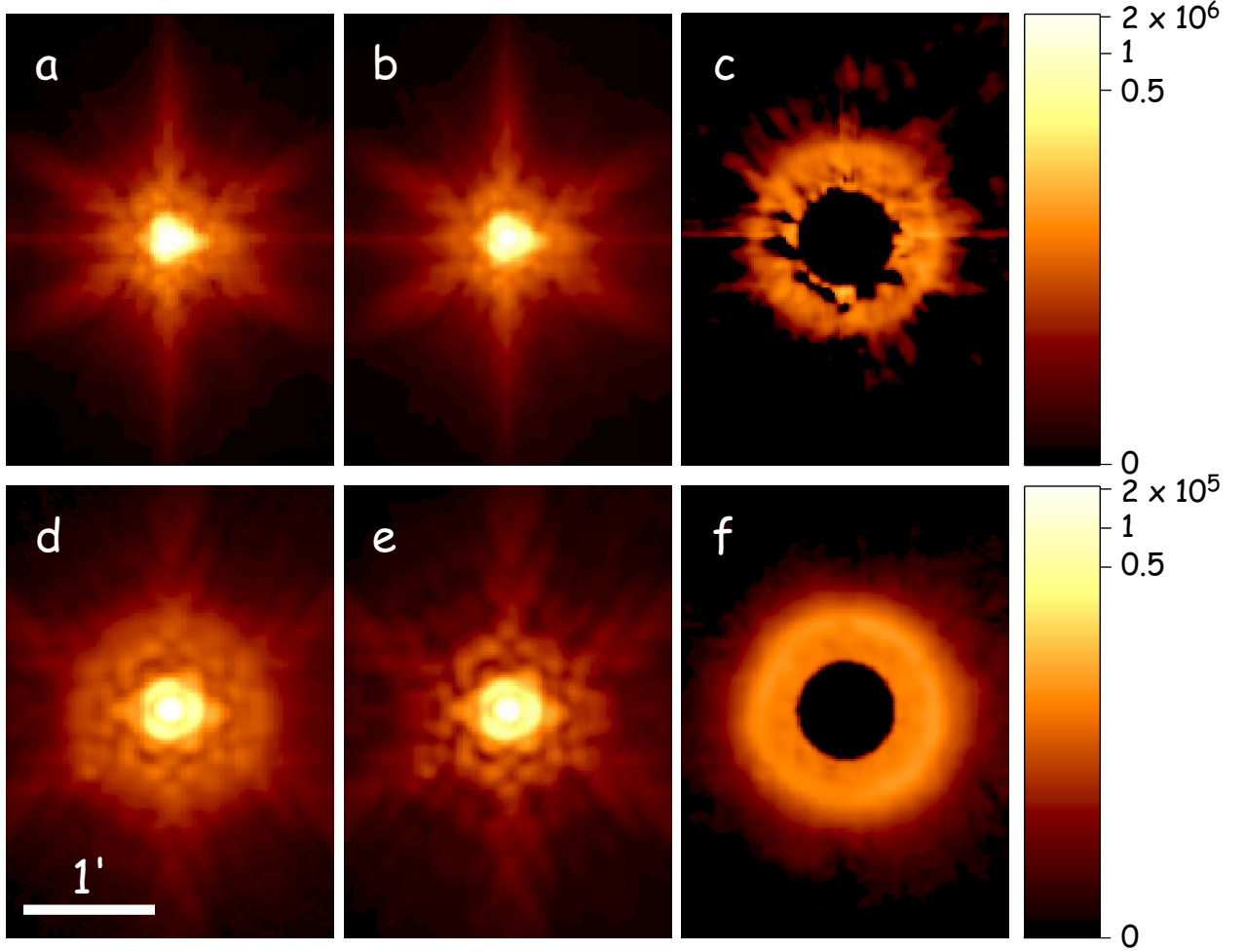


Fig. 1.— IRC MIR images of U Ant. The top row shows (a) the co-added image corrected for the artifacts, (b) the artifact-removed PSF pattern, and (c) the co-added image subtracted by the central star PSF for the L15 band. The bottom row (d, e, and f) shows the same images for the L24 band. The color scales are in units of ADU per pixel and the scale of the central-star-subtracted images is enhanced by a factor of 20 and 10 for the L15 (c) and L24 (f), respectively. For c and f, the central 20'' region is not plotted to show the shell structure clearly.

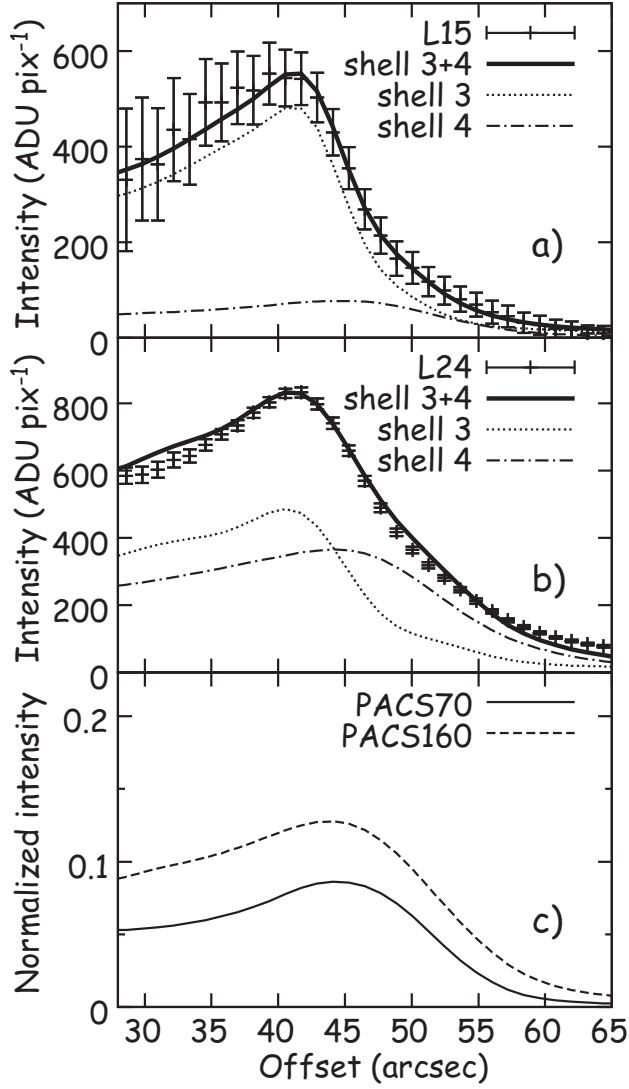


Fig. 2.— Radial brightness profiles (RBPs) of the detached shell of U Ant at (a)  $15\ \mu\text{m}$ , (b)  $24\ \mu\text{m}$ , where the profiles of the best-fit double-shell model are also indicated by the solid lines together with the RBPs of the two shells by the dotted and dot-dashed lines (see text for details), and (c) model profiles for PACS 70 (solid line) and  $160\ \mu\text{m}$  (dashed line) based on the two-shell model (see §4).

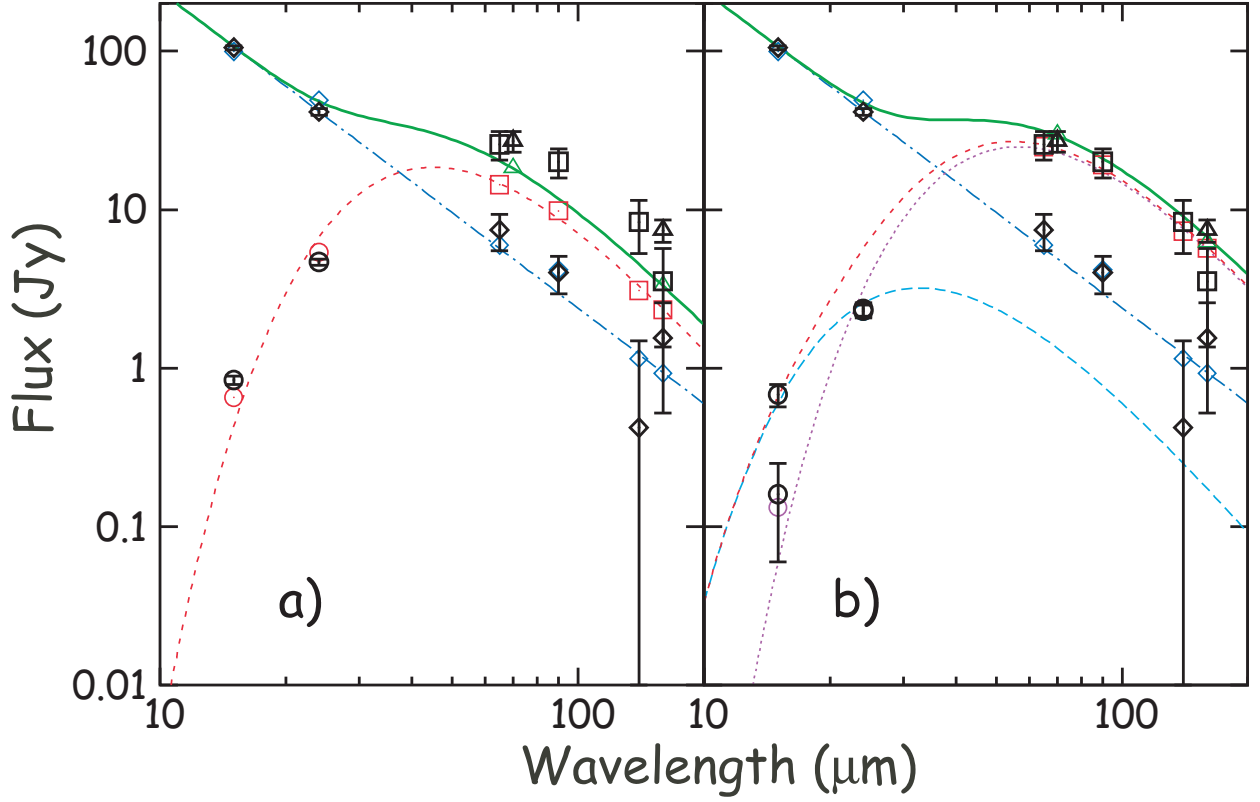


Fig. 3.— SED fit results: (a) single-temperature and (b) two-shell case. The green solid line indicates the total flux density of the best-fit model and the red dashed and blue dot-dashed lines indicate the shell and central source flux densities of the model, respectively. The light blue dashed and purple dotted lines in (b) indicate the models of shells 3 and 4, respectively. The black symbols with error bars indicate the observations, whereas the color symbols indicate the color-corrected model values of the lines of the same color, which should be compared with the observations. The circles and the squares indicate the shell emission ( $F_{\nu}^s$ ), the diamonds the central source emission ( $F_{\nu}^c$ ), and the triangles the total flux densities ( $F_{\nu}^t$ ) (see Eq. (1)).